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AGING AIRCRAFT WIRING: A PROACTIVE MANAGEMENT METHODOLOGY

by

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During the last years, military budgets have been dramatically reduced and the services have been unable to acquire sufficient new systems. Military aviation is one of the areas that have been severely impacted. The result is that the current fleet faces significant aging aircraft problems.

Aircraft wiring is one of the areas that have severly affected by the aging process. Recent accidents involving aging wiring problems and reduced operational readiness due to aging wiring have made clear that aging aircraft wiring presents a difficult and complicated problem for the military aviation. However, current maintenance practices fall short in successfully inspecting and maintaining wiring.

The purpose of this thesis is to provide a proactive management plan to deal with aging wiring. The objective is to come up with a systematic process in order to identify and prevent serious failures caused by electrical faults of wiring systems. This process will be based on the principle of Reliability Centered Maintenance (RCM).

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AGING AIRCRAFT WIRING: A PROACTIVE MANAGEMENT METHODOLOGY

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During the last years, military budgets have been dramatically reduced and the services have been unable to acquire sufficient new systems. Military aviation is one of the areas that have been severely impacted. The result is that the current fleet faces significant aging aircraft problems.

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I. INTRODUCTION

A. BACKGROUND

During the last years, military budgets have been dramatically reduced and the services have been unable to acquire sufficient new systems. Military aviation is one of the areas that have been severely impacted. The only way to meet the mission demands in a constrained funding environment is to extend the service life of selected aircraft.

There are many old aircraft (20 to 35+ years) that are the backbone of the operational force, some of which will be retired and replaced with new aircraft. However, for the most part, replacements are a number of years away. For many aircraft, no replacements are planned, and many are expected to remain in service another 25 years. For example, it will be at least another 10-15 years at best, before there will be a significant number of replacements for the F-16 A/C.

The aging of aircraft has resulted in extremely challenging problems dealing with the long-term effects of structural aging and repair, but what is the effect of aging on other systems? Until recently, the aging of electrical systems, and wiring specifically, received little attention. This is changing dramatically, in part due to a number of serious accidents involving wiring problems. Recent accidents in both the commercial and military aviation have made clear that the effects of age on aircraft wiring need to be examined in the same way as structures.

Wiring is the vital electrical and optical network that carries data, signals and power to and from the various systems. Wiring goes into every nook and cranny. In fact, wiring is embedded into the aircraft the way nerves are embedded into flesh.

Like all materials, wire ages and degrades over time. Vibration, moisture and temperature can adversely affect wiring characteristics. Shorts, arcing and open circuits are the results of wire insulation degradation which can be a serious flight safety concern. Wiring problems have often caused fires or aircraft systems malfunctions leading to aircraft loss.

Wiring-related problems are a leading cause of unscheduled maintenance hours for aircraft. A significant portion of aircraft maintenance man-hours is expended in troubleshooting wiring to effect repairs of avionics and weapon systems. However the maintenance philosophy is “fly to fix”. Aircraft wiring is not repaired unless it actually causes a system failure or is a safety hazard. Moreover today’s typical inspections are visual and they do not get to the heart of aircraft wiring problems. Obvious failures such as severed wires are detected but individual visual inspections do not reveal the slow but continuous erosion of wiring insulation that results from thousands of bumps and jolts over the aircraft lifetime.

B. PURPOSE

The purpose of this thesis is to provide a proactive management plan to deal with aging wiring. The objective is to come up with a systematic process in order to identify

and prevent serious failures caused by electrical faults of wiring systems. This process will be based on the principle of Reliability Centered Maintenance (RCM). Research will include an evaluation of the current maintenance philosophy for aging wiring, analysis of wiring from a RCM perspective, and will suggest a proactive management plan for dealing with aging aircraft wiring systems.

C. RESEARCH QUESTIONS

The questions that this thesis is posing and trying to answer are:

- How we define aging aircraft? What are the associated problems with aging aircraft?
- What is the current status in USAF, USN and commercial airlines with respect to aging?
- What are the functions and the characteristics of the aircraft wiring systems?
- What are the causes of aging wiring?
- What are the consequences of aging, in wiring systems?
- What is the current maintenance practice? Does it adequately address wiring problems?

- What is Reliability Centered Maintenance (RCM) and what are the potential applications to the problem of aging wiring ?

- What are the technical solutions that can facilitate a management plan for aging wiring based on RCM?

D. SCOPE

The scope will include: an analysis of the aging wiring problem and how it affects readiness and aircraft safety, an evaluation of the current maintenance practice for aging wiring, an analysis of the Reliability Centered Maintenance (RCM) philosophy, and a feasibility study of implementing a proactive and RCM-based, management plan for aging wiring. The thesis will conclude with a recommendation for applying this plan to aging aircraft fleets.

E. EXPECTED BENEFITS OF THIS THESIS

This study will provide the necessary information required to implement a proactive and Reliability-Centered-Maintenance based management plan for aging wiring. Expected results include increased operational readiness, reduction in maintenance costs and increased aircraft safety.

F. ORGANIZATION

Chapter II provides an introduction to the general aging aircraft problem. This chapter includes a description of the aging aircraft issue, an overview of the current status in the military and the commercial sector along with the initiatives that these parties have taken to deal with this problem.

Chapter III provides a description of the aircraft wiring, analyzes how aging affects it and what are the results of aging wiring, and provides an overview of the current maintenace practice concerning aging wiring.

Chapter IV describes the Reliability Centered Maintenance concept and how it can be applied in aging wiring, devises a proactive wiring maintenance plan and provides technical solutions that are based on RCM.

Finally, Chapter V provides the conclusions and recommendations of this research.

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II. THE AGING AIRCRAFT PROBLEM

A. INTRODUCTION

Both military and the commercial air fleets, face an impending crisis. Aircraft are getting older, and as they continue to age, problems resulting from aging aircraft will become increasingly more urgent. The military and the airlines continue to fly planes as they age, and many of these aircraft have already exceeded their economic design goal (generally considered to be the period of service, after which a substantial increase in maintenance costs is expected to take place in order to assure continued operational safety). Experience proves that high-cycle planes, even those that are well constructed and kept in good repair, are vulnerable to many problems such as structural fatigue, corrosion, system degradation, as they age. Age-related incidents may become commonplace and result in loss of aircraft, loss of mission and, most importantly, loss of human lives.

But, how someone can decide if an aircraft is old? What are the criteria in such a decision? No single criterion identifies aircraft as "old". The "age" of a plane actually depends on many factors. Measuring chronological age is one means of establishing the "age" of an aircraft. Considering the number of flight cycles a plane has accumulated is equally important in determining the wear on a plane. A complete flight cycle is composed of one take-off, pressurization, depressurization and landing, since these

activities typically place the most stress on an aircraft. Consequently, to obtain a true picture of the "age" of an aircraft, both the number of years and the number of cycles that a plane has flown are relevant factors. As aircraft age and cycles accumulate, aging problems will inevitably occur. Hence, the need for inspection and maintenance increases as aircraft grow older.[Ref. 1]

B. MILITARY FLEET

Any discussion of the wisdom of retaining instead of replacing capital equipment, such as aircraft, is usually based on economic considerations. For example, if the costs of maintaining the equipment exceed the capital, interest, and amortization charges on replacement equipment, the decision to purchase the replacement is straightforward. Often the replacement equipment offers an improved productivity as well.[Ref. 2]

In the case of military aircraft, operational readiness and safety-of-flight considerations also enter into the decision to repair or replace. Fortunately, inspection and maintenance procedures have been developed to reduce the likelihood of failures during the design service life. However, several political changes, including the end of the Cold War, have caused the military to change their approach to force management. Since the budget to develop new aircraft systems has been reduced, the only way to meet the mission demands is to extend the service life of some aircraft.

The U.S. Air Force has many old aircraft that form the backbone of the total operational force structure. The oldest are the more than 500 jet tanker aircraft, the KC-

135, that were first introduced into service more than 40 years ago. The B-52H bomber and the C-130 airlifter became operational 35 to 40 years ago. The F-15 air superiority fighter, the A-10 close air support aircraft and the E-3 (AWACS), 20 to 25 years ago. The F-16 multirole fighter and the KC-10 jet tanker are 15 to 20 years old. For the most part, replacements for these aircrafts are a number of years away and the program schedules continue to be constrained by and subject to the vagaries of annual funding cycles. For example, at best, it will be 15 to 20 years at least, before there will be a significant number of replacements for the F-16. The remainder of the aircraft mentioned above have no planned replacements and are expected to remain in service an additional 25 years or more.[Ref. 2]. Table 1 shows the current age status of the USAF fleet.

A/C Type	Avg Age (yrs)	Total A/C	A/C Type	Avg Age (yrs)	Total A/C
A/OA-10	15.8	220	F-16	7.1	802
B-1	10.3	77	EF-111	29.2	33
B-2	3.3	20	F-117	6.4	57
B-52	35.8	85	G-3	6.6	3
C-5	15.8	81	G-4	12	14
C-9	26.5	23	G-7	12	9
KC-10	12.7	59	G-9	10.6	4
C-12	18	34	G-10	2.6	1
C-17	2.7	34	G-11	2.2	2
C-18	11.4	6	H-1	26.5	70
C-20	9.9	13	H-53	24.9	46
C-21	12.7	76	H-60	8.4	59
C-23	12.9	3	RQ-1	0.9	2
C-25	6.9	2	T-1	2.9	179
C-27	5.4	7	T-3	2.6	110
C-130	25.1	306	T-37	34.2	419
C-135	35.7	300	T-38	30.2	471
C-137	21.3	6	T-39	36.6	3
C-141	31	141	T-41	27.5	3
E-3	17.8	32	T-43	23.5	11
E-4	23.3	4	U-2	13.6	28
E-8	1.2	2	V-18	13.5	3
F-4	27.9	3			
F-15	11.9	618	**Total**	**18.8**	**4,481**

Table 1. USAF Active Fleet, May 1998 From [Ref. 3]

The Navy faces a similar problem. The Navy currently operates over 2,100 aircraft that are over fifteen years old, 965 of which are more than 25 years old. Figure 1 displays the aging trend for the current fleet.

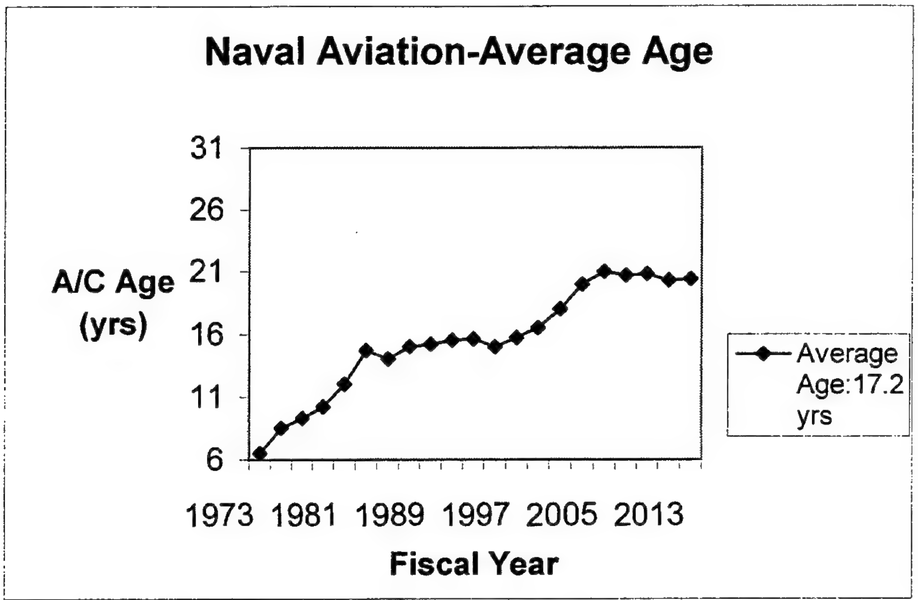

Figure 1. Aircraft Average Age Trend From [Ref. 4]

Some naval aircraft are over 30 years old, such as the CH-53D and the CH-46. Some others have replacements on the way, such as the F/A-18 E/F Super Hornet for the F-14 Tomcat and older F/A-18 C/D Hornets; the Boeing 737 for the C-9; the V-22 for the H-53 and H-46; and the CH-60 for the H-46.[Ref.5]. However, several platforms do not have replacements currently planned, and even the ones with replacements coming, will continue to operate for several more years before new systems come into service. Like the Air Force case, extending naval aircraft service life by controlling aging impacts is critical for future mission accomplishment.

The number of military operations during the last years, has been very high. Although the operational environment is very demanding, the number of aircraft has shrunk with the remaining force aging rapidly. Aging aircraft and its implication is a

relatively new topic and wasn't considered by the aircraft designers because they thought that aircraft and related systems would be replaced before age became an issue. Even aircraft that are relatively young are being stressed to their limits. Especially Navy aircrafts, that are flown under adverse conditions (salt water, catapult launches and hard landings), experience increased aging problems. For example, the F-18 community is expecting to spend $878 million over the next 12 years to conduct a service life extension program (SLEP) for 355 F/A-18 C/D aircraft.

As a result, military aviation readiness is falling. Figure 2 depicts the daunting trends for naval aviation, while Figure 3 shows the increase in maintenance man-hours per flight hour.

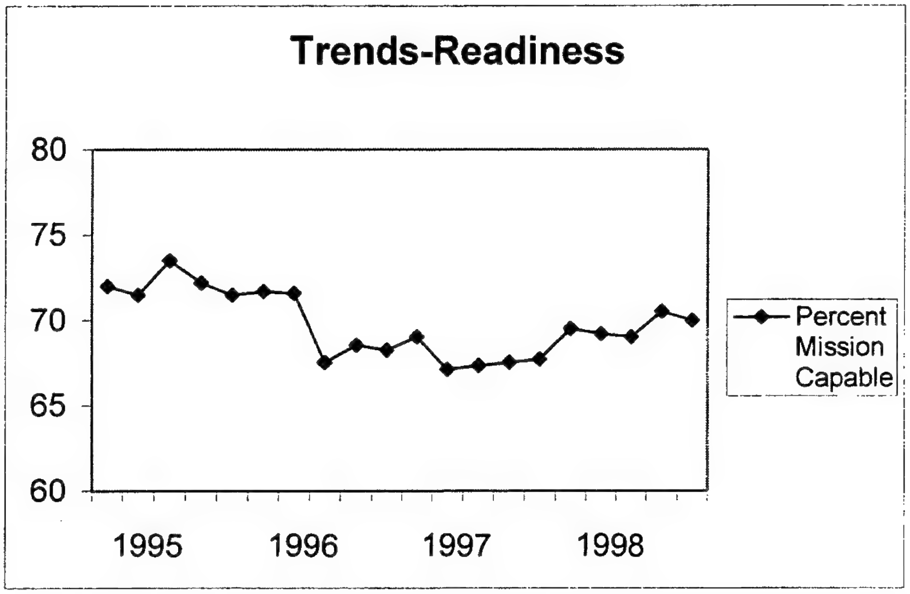

Figure 2. Readiness Trends From [Ref. 4]

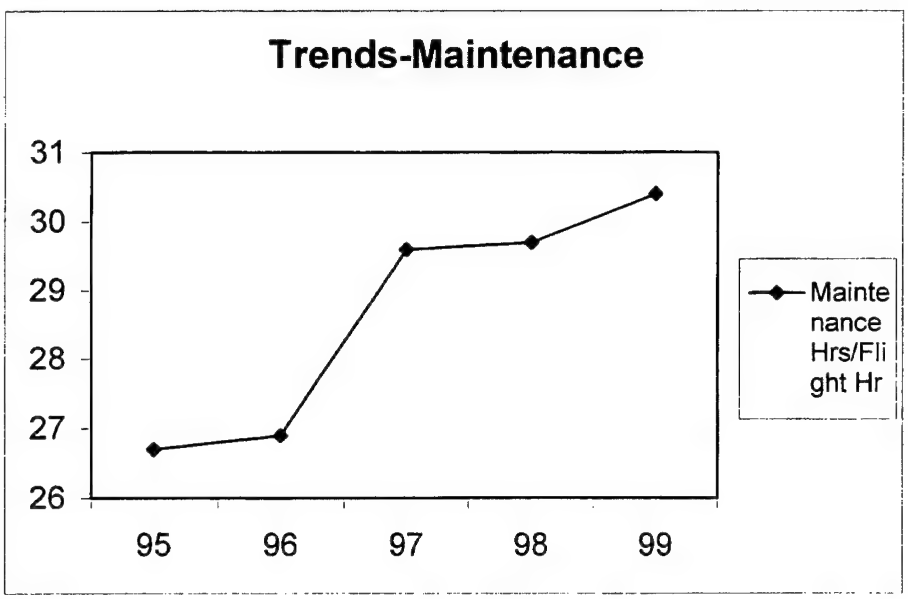

Figure 3. Maintenance Man-Hour Trend From [Ref. 4]

C. COMMERCIAL FLEET

Since deregulation of the airline industry, the rapid growth of U.S. air carrier passenger traffic has been accompanied by high demand and increased delivery times for new aircraft. The long lead time for the acquisition of new aircraft has thus forced the airlines to operate some of their aircraft beyond originally expected engineering life.

Various factors force airlines to operate airplanes beyond their economic design goals. New aircraft production cannot keep pace with industry growth and probably will not be able to match the demand in the near future. This lag in production has resulted, and will continue to result, in the extended use of numerous aircraft beyond their intended life spans. Due to backlogs in orders for new aircraft, delivery may be delayed for several years after the order is placed. Thus, to meet consumer demand, airlines continue to fly aircraft that they expected to retire. Furthermore, new planes are being used not to replace old aircraft, but to supplement the existing fleets, thus expanding the fleet to match passenger demand. Low fuel prices also make it economical to continue to use the older, less fuel-efficient planes rather than retire them.

The average age of the U.S. commercial air carrier fleet has increased from 4.6 years in 1970 to 18 years in 1999. The U.S. commercial fleet breakdown is presented in Figure 4. By early 1999, 41 percent of the fleet was at least 20 years old and nearly 800 more aircraft were rapidly approaching that age. In the past, 20-year-old aircraft were most often replaced by newer aircraft for airline service. However, this is no longer true and the number of 20-year-old aircraft is expected to increase. Although chronological

age alone is not a direct measure of potential aging problems, it can alert operators to problems when age correlates with high numbers of flight hours and flight cycles.

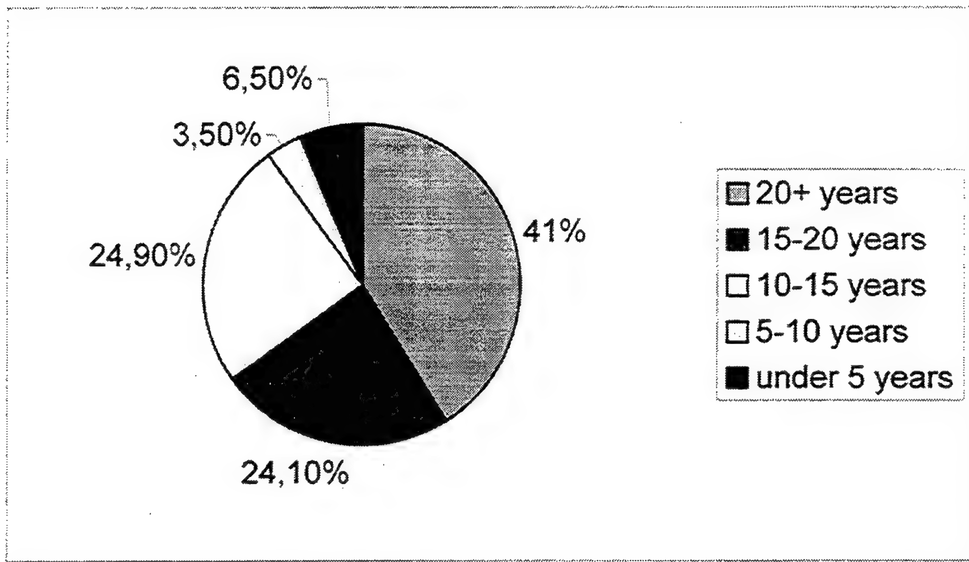

Figure 4. U.S. Commercial Fleet Age Breakdown From [Ref. 6]

D. JOINT INITIATIVES

As previously shown, both the military and the commercial aviation, experience urgent aging problems. Table 2 gives a clear picture of the extensiveness of the problem.

	Number Of Planes	AGE 10+Years	20+Years
Major U.S. Airlines	3696	90%	41%
International Airlines	3646	83%	36%
U.S. Cargo carriers	982	97%	81%
International cargo	95	96%	84%
U.S. Air Force	4421	71%	42%

Table 2. Ages of Aircraft Serving in Composite Fleets, as of 1999 From [Ref. 7]

The designers of the aircraft in service today, would have never dreamed these planes would be operational for so many years. Indeed, not much thought was given to the aging issue, because the aircrafts were to have been retired long before aging problems became significant.

In order to effectively deal with aircraft aging, the military and the commercial sector have joined forces. The Navy, Air Force, Federal Aviation Administration (FAA), NASA and private aerospace industry are jointly attempting to insert technology and improve maintenance/support actions to address the aging aircraft issue. Various organizations and joint programs such as the White House Commission on Aviation Safety and Security (WHCSS), the Air Transport Association's Aging System Task Force (ASTF), the FAA Aging Aircraft Task Force, the Air Force Aging Aircraft Office, the

NAVAIR aging aircraft Integrated Product Team (IPT), the inter-agency/inter-service aging aircraft planning (JACG), have been developed. Furthemore, NASA, FAA, Navy and Air Force have jointly held five conferences to address the aging aircraft problem. These initiatives demonstrate the seriousness of the aging problems and the coordinated attempts of government and industry.

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III. AGING AIRCRAFT WIRING

A. INTRODUCTION

In dealing with the problems of extending the life of aging aircraft, most emphasis seems to be placed on structural issues. Indeed, the aging of aircraft has resulted in extremely difficult problems dealing with the long-term effects of structural aging and repair, but what is the effect of aging on other systems? Until recently, wiring has often been forgotten or treated as an afterthought. The aging of electrical systems, and wiring specifically, received little attention. This is in the process of changing dramatically, in part due to a number of serious accidents involving wiring problems. Recent accidents in both commercial and military aviation have made clear that the effects of age on aircraft wiring need to be examined in the same way as is done with structures.

B. AIRCRAFT WIRING

1. General

One way to realize what wiring performs in an aircraft is to compare it with veins. Think of the human body. How important is blood to the body? How is blood distributed to all the living organs in order for a human being to function, cope with the environment and survive? The blood is distributed to the living organs by veins. Let's compare the

veins to wire for an aircraft. An aircraft needs electrical energy to function like the human body needs blood. This electrical energy is distributed by wiring.

Bundles of wire carry the electrical energy like veins carry the blood. There are arteries, big and small carrying blood, like power wire busses carry power. Power busses are like major arteries. Individual wire bundles for specific controls, instruments, lights and electronic items are like small arteries. They all perform vital functions in the control of the aircraft during all kinds of environmental conditions. If a vein carrying blood, is damaged or cut, then then there is a limited period of time for a person to react before he or she experiences weakness, loss of functionality for organs and possibly eventual death. If any of the wire bundles in an aircraft, experiences a fire, the plane has a limited time to respond to damage to the wiring harness. The aircraft experiences weakness, loss of functionality of controls and vital instruments before losing altitude, speed and results in sudden death (crash).

Wiring is, thus, the vital electrical network that carries the data, signals and power to and from systems. Wiring goes into every nook and cranny. As previously shown, it is embedded into the aircraft the way veins and nerves are embedded into flesh. This provides the opportunity to monitor and interrogate the health status of systems and framework components.

Electrical wire consists of a conductor that is encased in a protective layer of insulation. Wire is routed throughout an aircraft in a series of bundles with clamps and connectors. Safe routine practices include measures to prevent wires from wear, abrasion,

contamination and contact with other components; to gently bend and turn wires during installation to prevent cracking of the insulation and to physically separate wires from systems whose signals may interfere with one another.[Ref. 8]

The bulk of aircraft wiring failures are attributed to broken wire and insulation damage. Table 3 shows the kinds of failure seen on a typical Air Force fighter aircraft.

Broken Wire	46%
Insulation Chafing Damage	30%
Outer Layer Chafing	14%
Failure in Connector	10%

Table 3. Wire Failure Data for a Typical Fighter From [Ref. 9]

2. Insulation

Wiring insulation is the first line of defense. It provides a protective barrier between a conductive wire and other conductive objects, such as the airframe or a nearby conductor. Insulation can be made very thick if necessary. But aircraft wiring needs to be thin to conserve weight, pliant to bend without cracking, abrasion resistant, and have high dielectric (insulating) strength. Historically scientists have had difficulty in designing and manufacturing insulation that simultaneously meets all requirements. Soft, flexible wiring tends to erode more easily than a hard surface. If it is too soft, the conductor will push through due to stress at bends. Eventually, the insulation becomes cracked or worn

through. A single arc from a worn or cracked spot can cause arc tracking where the insulation burns along a length of wiring exposing more of the conductor. Eventually the problem releases enough current to cause the breakers to throw, but not before many wires have been affected and toxic fumes are spread by convecting air currents.[Ref. 10]

Most military and commercial aircraft produced over the last twenty years use a wire insulation construction based on either military specification MIL-W-81381 or MIL-W-22759. The insulation materials used are principally aromatic polymide (also known as Kapton) or cross-linked ethylene tetrafluoroethylene (EFTE).

The problem of smoke and fires is particularly acute in old wiring insulated with aromatic polymide insulation (Kapton) which appeared to meet requirements of light weight and high dielectric constant. But Kapton fails the test of time. This particular insulation is composed of a substance with loosely bonded benzine molecules that eventually turn into carbide crystals. When moist or wet, carbide crystals react with moisture to form a flammable gas [Ref. 10].

The Navy, which commonly operated in the harshest of environments, was one of the first users to notice the problems associated with Kapton insulation and banned Kapton's use. Between 1996 and 1998, the DoD Single Process Initiative, obliged McDonnell Douglas to standardize all military aircraft production on composite insulation. Composite wire saved weight, reduced part number complexity and improved safety.[Ref. 11]

3. Circuit Breakers

The primary device for protecting an aircraft from the hazards of electrical malfunctions is the circuit breaker. Its role is to protect wire from damage due to current overloads. Circuit breakers are capable of responding to the thermal effects of the current carried by the wire and are flexible enough to work with a wide variety of loads in multiple platforms under diverse environments. Aerospace circuit breakers are based on the principle of sensing heat. They use thermal elements designed to protect wiring insulation systems based upon historical insulation aging-versus-temperature data. They are designed to protect the wiring circuits by opening automatically prior to damage occurring through excessive heating under overload conditions [Ref. 12].

C. CAUSES OF AGING WIRING

1. General

Wire systems link electrical, electro-mechanical and electronic systems. Wiring has emerged as vital in the control and safety of these systems, due to their increasing complexity. However, all electrical wire systems are subject to aging: the progressive deterioration of physical properties and performance of wire systems with use and with the passage of time.

Wire degradation is cumulative over time. For instance, in Figure 5 the correlation between flight hours and the occurrence of wire degradation, is clearly revealed. As an aircraft ages, the number of wire defects increases.

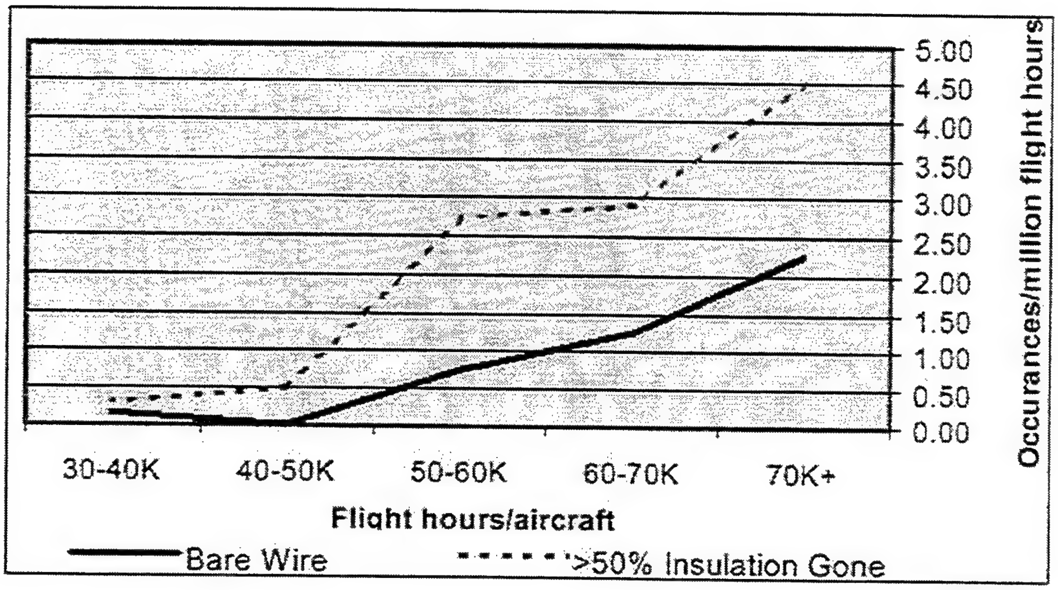

Figure 5. Age-Related Wire Failure From [Ref. 9]

The causes of the aging wiring can be summarized as follows:

- Enviromental factors
- Wiring Design
- Wiring Installation

2. Environmental Factors

Environmental damage is defined as degradation due to exposure to the atmosphere, vibration, heat, water intrusion, corrosion and other such effects.

Vibration is one of the factors affecting wire aging. Vibrations that occur naturally in flight cause wires to rub against aircraft parts, and against themselves. This protracted rubbing causes the protective insulation to wear thin and eventually expose the core. Vibration is also, not constant throughout the frame of the aircraft. It varies greatly and as such it is affecting the wiring running through those areas differently as well. Wheel wells, engine compartments, areas near the air-conditioning packs all have different vibration cycles and yet the current approach to wiring does not take those differences into account.[Ref. 13]

Moisture is another contributor to aging wiring. Most insulation material is very complex long chain polymer and moisture accelerates changes to this complex polymer which decreases the insulation qualities over a short period of time.[Ref. 13]

Temperature is another player. Besides the internal overheating, there is also the external heat coming from just about any device on aircraft. A great amount of energy is used in aircraft, and energy is heat.

Wiring connectors can also be affected by environmental factors. The connectors are usually good for about 500 open/close cycles. Over the course of twenty years, it is quite likely that some high failure units will cause this limit to be exceeded. As the connectors are opened to allow access, moisture often enters. On closure the moisture

reacts with the metals of the connector. Aluminum/nickel plated connectors corrode easily. But, even stainless steel housings can corrode over time. Corroded connectors crack and break to expose wiring to the elements and the breakage results in loose or intermittent connections.[Ref. 10]

Finally, the severe launch, recovery and salt water environment in which Navy aircraft operate compounds the problem further.

3. Wiring Design

Some of the more common answers, that one can get when asking people dealing with airplanes for their opinion on wiring, are:

- Wire is wire. It is never different.
- Wiring is a necessary evil.
- Wire just connects the pieces that "really" do something, like radios and computers.
- Anybody can design wiring.
- Wiring costs too much.
- Wiring adds too much weight.
- Wiring can ruin the electro-magnetic interference (EMI) test results.

- Wire consumes all the maintenance hours.

- The only thing ever new about wiring is a new way that it can fail.

All the above comments show that wiring, at the basic level, is not an overly complicated engineering discipline. It is not difficult to understand continuity, electrical isolation, and that most connectors adhere to "righty-tighty, lefty-loosey." Just about everyone can design a wiring harness but will it work long, work well, be cost effective, be light, not corrode, be maintainable ? This is where wiring design as a specialty matters, and where wiring design can have a big impact on the aging aircraft situation.[Ref. 14]

In 1978, a standard carrier-based F-14 Tomcat fighter had approximately 90,000 feet of wire in its wiring system. A Boeing 747 had approximately 500,000 feet of wire. According to studies conducted by NAVAIR, this would translate to roughly 786 and 4,366 pounds respectively, not including connectors and supporting hardware. This imposed high pressure in wiring design. The pressures on both military and commercial operators to reduce weight for advances in performance and range have made the wiring system an easy target for weight reduction initiatives [Ref. 15].

These weight reductions did not come free. They had their impacts in both wiring design and wiring maintenance. Wiring was relegated to whatever space was left over when hydraulic lines, control rods and cables, avionics boxes and other equipment was installed. In one case the generator feeder wires were installed riding against the structure and hydraulic lines for a good distance. These conditions required significant added chafe protection. [Ref. 15]

Some other examples of weight reduction initiatives included reduction or elimination of the required slack in wiring and reduction of insulation thickness and conductor size. The result was a number of problems due to lack of slack provisions, wire and conductor breakage and breakage of previously undamaged wire while trying to locate a fault in another wire (maintenance handling difficulties).

Another problem with wiring design is that every aircraft misses some beneficial new innovation during its development process because it is "too late" to get it in the design.

For example, aircraft that were designed 35 years ago are penalized by the fact that wire insulation used was very thick (.015 in plus) compared to wires available just a short time later. With minimum gauge practices in place at the time (typically 22 gauge) these factors combined to make for a heavy wiring system. The aircraft still in service from this time carry this added weight around the world every day. In an aircraft like a B-52, it is quite possible that this weight penalty could amount to thousands of pounds if any significant amount of the original wiring is still installed.[Ref. 14]

Age of design has an even larger effect on connectors. Contact gauge size minimums have a tremendous impact on connector count. Many older aircraft and avionics were designed when connectors were available with only 16 or 20 gauge contacts. Pin density of a 20 gauge connector is half of a 22 gauge type. Going to 16 gauges halves it again. Aircraft disconnects can be greatly reduced by a redesign [Ref. 14].

4. Wiring Installation

Installation of wiring also has a large effect on wire aging. Most of the current insulation types are unable to withstand tight radious bends, yet in today's aircraft, there are thousands of examples of this type bending. The clamping and bundling devices also add to stress and strain on the insulation.

Another problem with wiring installation is that since wiring is not treated as a system, it is therefore relegated to whatever space is left. The result is poor location of terminals, connectors and junction points and the relative size of the maintenance tools.

D. AGING WIRING EFFECTS

1. General

As previously dicussed, aircraft wiring can be compromised by several factors. Wiring design and installation, and environmental factors can all contribute to premature aging wiring. Aging wiring can severely impact the aircraft safety. Two are the main effects of aging wiring: short circuit and arc-tracking.

2. Short Circuit

When the protective layer of insulation on a wire is compromised and the conductor is exposed, the potential exists for a hazardous electrical system malfunction caused by a short circuit . A short circuit occurs when electricity takes an unintended path. For example, condensation and other conductive materials that are sometimes found

on wire bundles can bridge the gap between a wire conductor and adjacent metallic structure. When electrical current follows the unintended path to the metallic structure, a short circuit that could interrupt the function of an electrical system occurs. Short circuits can transfer power to adjacent wires or draw an excessive current from the power source, overheating wires and creating fire hazards.[Ref. 8]

3. Arc Tracking

Electrical arcing is a type of short circuit in which high current crosses a gap, emitting sparks. The sparks include molten material from the wire conductor as it is vaporized by the high energy discharge, producing extreme localized heat. The arcing could ignite flammable products in the area and could potentially initiate an explosion [Ref. 8].

Arc tracking occurs when the insulation material chars. The charred insulation is conductive, can sustain and propagate an arc along the length of a wire, and may flash-over to consume adjacent wire insulation or other combustible material. With the exception of intermittent operating anomalies, neither the pilot nor the maintenance personnel will have any direct indication that conditions conducive to arc tracking are developing.

The arc tracking or "ticking fault" as it is often called, has a time duration of just a few milliseconds. Typically the voltage will drop to some mid level point while the amperage will increase by a factor of ten or more. This is a discharge of a great amount of

localized heat and energy yet because of the short duration of the arcing event, current circuit breaker design will not protect against this type of failure. Although circuit breakers do protect against the electrical overheating of wires, they do not protect against arcing faults because they are designed to activate based on heat input. Arcing develops high energy, but in a very short period of time. Eventually, the arc tracking process will increase to a point where it could cause catastrophic failure of a number of wires and systems.

4. Results

Both the short circuit and the arc tracking effects can lead to loss of critical aircraft systems, on board fires and loss of an aircraft. Arc tracking, especially, is very dangerous and has been implicated in many accidents: Apollo 1, Philippine Air Lines 737, U.S. Navy Aircraft, TWA 800 and Swiss Air 111 [Ref. 13].

Moreover, from July 1995 to December 1997, the U.S. Navy experienced 64 in-flight electrical fires. 80 to 90% of those fires, were attributed to arc tracking [Ref. 16]. Figure 6 and 7 show the degree of damage that an arc tracking can cause.

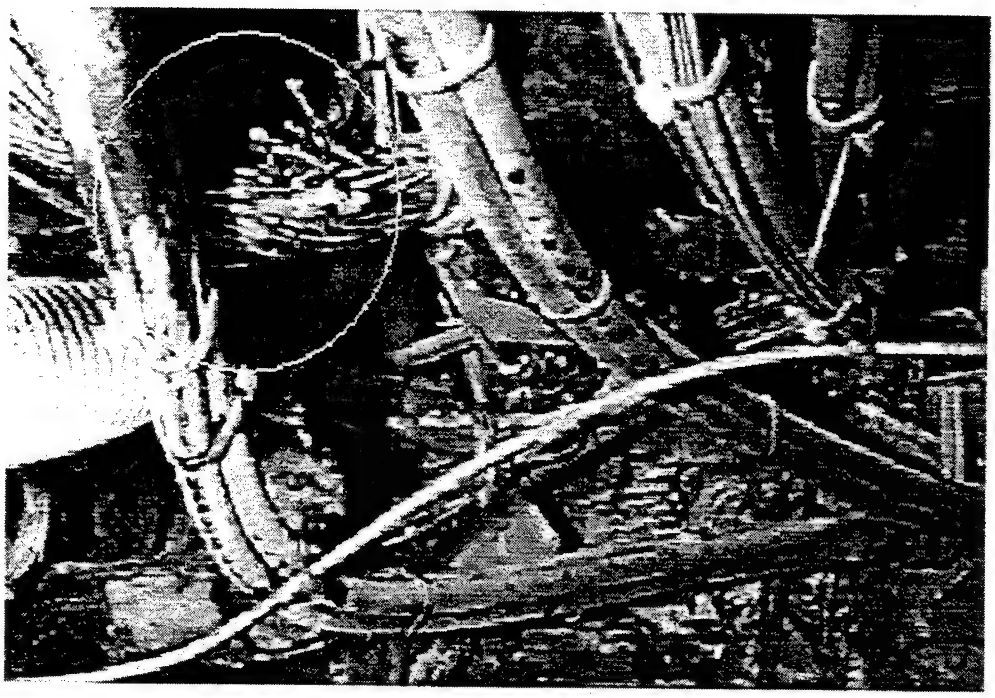

Figure 6. The Effects of an Arc-tracking Fire Supported by Moisture   From [Ref. 13]

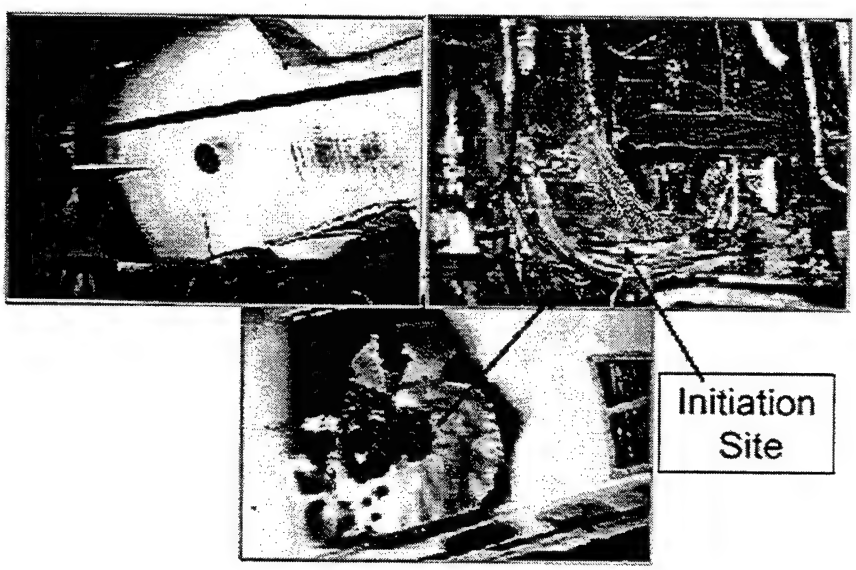

Figure 7. Wiring Failure Resulted in an In-Flight Fire   From [Ref. 17]

It is obvious that aging wiring constitutes a major threat to aircraft safety and readiness. Thus, wiring should receive the same attention as structure when dealing with aging aircraft problems. The maintenance process should address aging wiring issues and methods to proactively manage wiring.

E. CURRENT MAINTENANCE PRACTICES

1. General

The wiring systems have avoided examination unless they were determined to be casual in a mishap. The predominant maintenance philosophy for wiring, is “fly to failure”. Once it has failed, it is then repaired or replaced and the aircraft returns to service.

An analogy that can be used to describe the current situation, is one that involves a person that goes to a surgeon. This person has developed a specific symptom and visits the surgeon to have a major surgery performed. Then the surgeon and his team would examine the symptom and the affected area and perform the surgery. But the surgeon would not go into other areas and perform surgery without a symptomatic cause or purpose. The same can be said about wiring maintenance. The technicians will not examine wiring systems without any symptomatic indication of a problem, fearing that they would cause more damage. Rather, they will let the wiring systems remain untested until there is a wiring failure.

Wiring system maintenance is an organizational level task due to the relative permanence of wiring harness and cable installations. A significant portion of total aircraft maintenance man-hours is expended in the troubleshooting of wiring to effect repairs of avionics and weapon systems. Wiring troubleshooting is still a "hands on" art, with very little having changed in the last forty years. In fact, advances in avionics systems, such as Buit-In-Test (BIT) have hampered or even mislead technicians if the fault turns out to be in the system wiring. Wiring repair is so costly that some aircraft wiring is not being repaired unless it actually causes a system failure or is a safety hazard.[Ref. 18]

2. "O" Level Wiring Maintenance

Operational level maintenance is performed at the flight line. Most aircraft systems have two types of tests, operational and fault isolation tests. Operational tests run on an aircraft without modifying the basic operational configuration. Fault isolation tests change the aircraft configuration to provide more observability into the system. The symptoms of a failure for an aircraft can be classified into three categories: 1) the symptoms can be reproduced at the flight line, 2) the failure symptoms can only be observed in flight, 3) the failure symptoms were a result of some transient external interference and the system is functioning properly. If the failure is a type two or a type three category, the only way to verify the repair with absolute certainty is fly the aircraft and recreate the conditions that caused the failure to occur. The third class is important

because any removal action will result in a ReTest OK because it is impossible to dinstinguish between the second and the third classes when the failure is reported.[Ref. 18]

Troubleshooting faults using technical manuals or electronic technical data assumes that all failures are category one failures, and immediately jumps into a fault isolation procedure without verification of the actual presence of the failure. There may be a fault reporting code but this is an indication that a fault was observed by the BIT system and may have momentarily exceeded an established threshold. Diagnosing a system with no failure present will result in removing and replacing a functioning Line Replaceable Unit (LRU). This LRU will then ReTest OK at the intermediate or depot level. Because fault isolation procedures do not handle the second and third class failures, no mechanism other than pilot observation is established to track possible class two and three failures over multiple flights. Pilots are not always capable of detecting and tracking wiring fault anomalies.[Ref. 18]

Electronic systems are plagued with a rising number of "no fault found" problems. The root cause is removal of several good units in the course of troubleshooting an electronic unit which appears to be malfunctioning. Military experiences indicate that two of three removed units test to be in proper working order. The repair personnel spend many extra hours trying to find the problem that does not exist. False removals drive up the cost of support as many expensive units constitute a work-in-process inventory, causing the need for more spare units.[Ref. 10]

The failure reporting system is also a major concern. Current coding systems do not treat wiring as a system and do not give specific details on failures encountered. There is no Fault Isolation manual or fault tree, for wiring fault isolation. The technicians are on their own to develop a strategy to diagnose the wiring.

Problems in wiring also introduce ambiguities which make the isolation of root cause, even more difficult. Often there are more than one wiring harness segments from the power source to the affected unit.[Ref. 10].

Wiring repair is also complicated by the fact that many repairs performed are not "as good as new". A large number of splices, extra wire and tapes exist in today's wiring systems. These repairs are permanent in nature: they stay with the aircraft until the harness is replaced as part of a major upgrade. In most cases, these repairs stay with the aircraft throughout its service life. [Ref. 14].

Another problem is lack of knowledge of wire selection criteria, ordering procedures and replacement parts. The current philosophy is: "wire is wire, use whatever you find". This situation is a result of inadequate training, too many wire types and lack of standardization between aircraft. When replacement parts are difficult to get, the technical personnel use whatever is at hand.[Ref. 15]

Thus, it is not difficult to imagine that troubleshooting wiring is a maintainer's worst nightmare. It is not unusual to take several hours to find intermittent shorts and opens in aircraft wiring. The process usually requires a cart full of electronic equipment, extensive training and years of job experience [Ref. 10].

3. Visual Inspections

In July 1998, the FAA announced their Aging Transport Non-Structural Plan. The findings section of this plan includes the following statement, concerning current wiring maintenance practice:

> Current maintenance practices do not adequately address wiring components (wire, wire bundles, connectors, clamps, grounds, shielding). Inspection criteria is too general. Typically a zonal inspection task card would say to perform a general visual inspection. Important details pertaining to unacceptable conditions are lacking...Under current maintenance inspection practices, wire is inspected visually. Inspection of individual wire in bundles and connectors is not practical because aged wire is stiff and dismantling of bundles and connectors may introduce safety hazards. Wiring inside conduits is not inspectable by visual means... The current presentation and arrangement of standard pratices make it difficult for an aircraft maintenance technician to locate and extract the pertinent and applicable data necessary to effect satisfactory repairs. Under current maintenance philosophy, wire in conduits is not inspected. A review of incident reports and maintenance records indicate current reporting system lacks visibility for wiring making it difficult to assess aging trends.[Ref. 3]

The above paragraph clearly indicates that visual inspection, which is the current practice for both the DoD and FAA, has inherent disadvantages and is not the most efficient way of wiring maintenance.

Today's typical wiring inspections are visual and they do not get to the heart of aircraft wiring problems. Obvious failures such as severed wires are detected, but individual visual inspections do not reveal the slow but continuous erosion of wiring that results from thousands of bumps and jolts in the aircraft's lifetime. The bulk of electrical test and checkout is performed manually. These activities, in many cases, still involve pin

to pin tests by technicians with voltmeters. This type of testing is slow, expensive, error prone and unable to detect many of the anomalies. As previously mentioned, current practice dictates responding only when a failure has already occurred. The extent of electrical anomalies in operational aircraft is, in fact, largely unkown.[Ref. 3]

Many cracks in the insulation cannot be identified by visual inspection. These cracks are often smaller than a human hair but can nonetheless cause operational problems or loss of an aircraft. Thick bundles of wire conceal most wires and their faults from view. Wire insulation may look to be in perfect condition, but as it ages, it becomes weak and prone to damage.[Ref. 19]

Visual inspection cannot account for wiring that is placed high in the aircraft, only accessible with high lift rigs. Adequate lighting and visual acuity are essential to see a tiny pin-hole exposing bare wire. But some wiring runs through dark hidden areas where visual inspection is just not possible. Also wires in bundles are wrapped in tape and covered with coaxial metal sheathing. These harnesses are impossible to inspect visually. In fact, the twisting and pulling caused when disconnecting wiring for visual inspection may cause more problems than it finds.[Ref. 10].

There are also many parts of the aircraft that never get touched, but they are no less problematic. The dust and chaff that are collected in those areas, create an an excellent cause for sparks. Hydraulic fluids and other ingredients get also collected in and around wire bundles. This condensation is intensely caustic to most kinds of insulation. It

is interesting that one of the Navy and FAA directives call for cleanliness improvement within aircraft.[Ref. 7].

4. Summary

Aging wiring in military aircraft has been a problem for a number of years. The philosophy of wiring design for many in service aircraft today is that it would outlast the aircraft, would not need to be replaced, and therefore was not designed in modular fashion or for ease of maintenance. However, as wiring accumulates increased operational time and increased stresses due to aging effects, the rate of failure gradually increases the need for maintenance. But as already discussed, current maintenance practices fall short in successfully inspecting and maintaining wiring. There is an apparent lack of an effective and efficient methodology to manage and maintain wiring system anomalies prior to flight.

Managing aging wiring should focus on the management of wiring, as opposed to the waiting for failures to occur. There is an urgent need for a proactive management plan capable of preventing wiring failures, thereby ensuring aircrew safety and mission completion

Chapter IV suggests such a plan, based on the concept of Reliability Centered Maintenance.

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IV. RELIABILITY CENTERED MAINTENANCE OF AGING WIRING

A. INTRODUCTION

As already discussed, current maintenance practices fall short in successfully inspecting and maintaining wiring. There is a need for an effective and efficient methodology to manage and maintain aging wiring system anomalies.

In this Chapter a proactive management plan for dealing with aging wiring, will be presented. The objective is to come up with a systematic process in order to identify and prevent serious failures caused by electrical faults of wiring systems. This process will be based on the principle of Reliability Centered Maintenance (RCM).

B. RELIABILITY CENTERED MAINTENANCE

1. Background

Reliability Centered Maintenance (RCM) was a maintenance concept developed in the airline industry during the late 1960s. Keeping a fleet of aircraft in service is a maintenance-intensive effort. Performing preventive maintenance (PM) on the fleets took many resources. Airline companies wanted to see if they could maintain their fleets at the same level of quality at a lower cost. A strong correlation between age and failure data did not exist. This indicated that time-based PM was inefficient for the majority of equipment.[Ref. 20]

A new RCM program incurs an initial investment to obtain technological tools, training, and equipment condition baselines. This initial increase in maintenance costs due to RCM is short-lived. The cost of reactive maintenance decreases because failures are prevented and condition monitoring (CM) replaces preventive maintenance tasks. This results in a reduction in both reactive maintenance and total maintenance costs. A further cost savings from adopting RCM is that the program obtains the maximum use from equipment. RCM allows maintenance managers to replace equipment based, not on calendar, but on actual equipment condition. This approach to maintenance results in extending the life of the equipment.[Ref. 20]

In addition to PM, RCM recognizes other maintenance strategies including run-to-failure, predictive maintenance, and proactive maintenance. Each maintenance strategy suits a different equipment type.[Ref. 20]

RCM can be defined as an approach to maintenance that combines reactive, preventive, predictive and proactive maintenance practices and strategies to maximize the life that a piece of equipment functions in the required manner. RCM does this at a minimal cost. In effect, RCM strives to create the optimal mix of an intuitive approach and a rigorous statistical approach to deciding how to maintain parts and equipment.[Ref. 21]

The key to developing an effective RCM program lies in effectively combining the intuitive and statistical approaches. Intuition and statistics each have strong and weak points. Intuition is an effective tool when applied judiciously. However, if applied

without serious reflection and review, it can result in arbitrary solutions to the problem. A rigorous statistical approach has its limits, too. The first one is cost. Developing and analyzing an amount of data sufficient to provide a statistical basis is an expensive task. There is also the danger of the "analysis paralysis" pitfall. The more one is examining a problem, the more data it seems are required to solve it. The second limit is applicability. Statistics often do not tell the whole story. Data do not always produce definite trends, since there may be none.[Ref. 21]

RCM analysis carefully considers the following questions:

- What does the system or equipment do?
- What functional failures are likely to occur?
- What are the likely consequences of these functional failures?
- What can be done to prevent these functional failures?[Ref.21]

2. RCM Principles

The primary RCM principles are:

- RCM is concerned with maintaining system functionality. RCM seeks to preserve system or equipment function, not just to maintain a piece of machinery's operability for operability's sake.

- RCM is system focused. It is more concerned with maintaining system function than individual component function. The question asked continually is: Can this system still provide its primary function if a component fails?

- RCM is reliability centered. RCM treats failure astatistics in an actuarial manner. The relationship between operating age and failures experienced is important.

- RCM recognizes design limitations. A maintenance program can only maintain the level of reliability inherent in the system design. No amount of maintenance can overcome poor design. This makes it imperative that maintenance knowledge be fed back to designers to improve the next design.

- RCM is driven by safety first, then cost. Safety must be maintained and always comes first in any maintenance task.

- RCM defines failure as an unsatisfactory condition. Under RCM, failure is not an option.

- RCM tasks must produce a tangible result. The tasks performed must be shown to reduce the number of failures or at least to reduce the damage due to failure.

- RCM is an ongoing process. There is a feedback loop which is an inherent part of the RCM process. Maintenance personnel gather data from the successes/failures and feed these data back to improve future maintenance policies and system design. This feedback also includes changing old specifications that have been proven inadequate or incorrect, performing failed-part analysis, and performing root-cause failure analysis.[Ref. 21]

The most important from the above characteristics is that RCM is an ongoing process. When viewed in a strategic management model, as in figure 8, RCM is at the core of this model. The tasks of evaluating and selecting strategies and then establishing policies and objectives, are both parts of RCM. RCM is involved in strategy formulation and implementation and is a dynamic system with continuous feedback to facilitate continuous improvement.

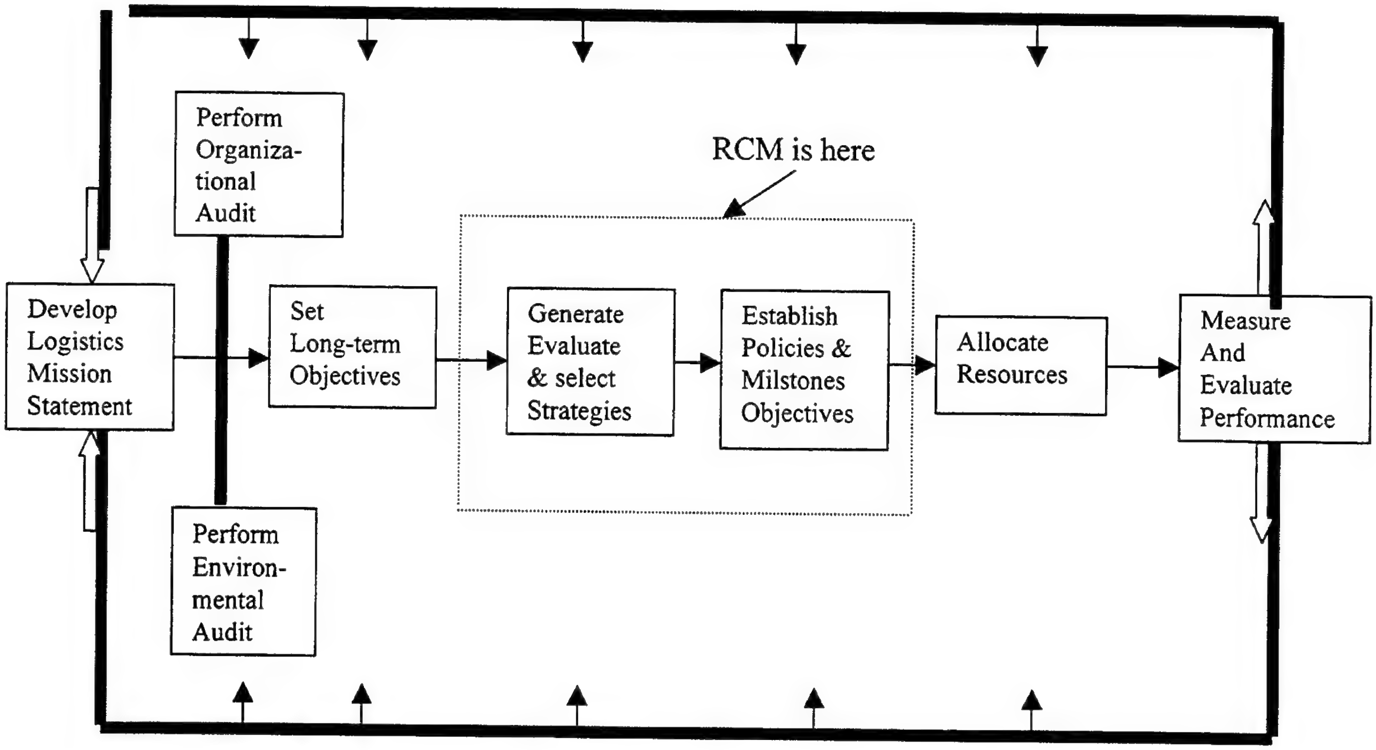

Figure 8. Strategic Management Model From [Ref. 22]

3. RCM Benefits

- Reliability. The primary goal of RCM is to improve equipment reliability. This improvement comes from constant reappraisal of the existing maintenance program and improved communication between maintenance supervisors, maintenance mechanics and equipment manufacturers. This improved communication creates a feedback loop (as shown in figure 8) from the maintenance mechanic in the field all the way to the equipment manufacturers.[Ref. 21]

- Cost. Due to the initial investment required to obtain the technological tools, training, equipment conditions baselines, a new RCM program typically results in a short-term increase in maintenance costs. The increase is relatively short-lived. The cost of reactive maintenance decreases as failures are prevented. The net effect is a reduction of reactive maintenance and a reduction in total maintenance costs.[Ref. 21]

- Improved logistics support. The ability of a condition monitoring program to forecast certain maintenance activities provides time for planning and obtaining replacement parts before the maintenance is executed.[Ref. 21]

- Readiness. A RCM program takes into account the priority or mission criticality. The flexibility of the RCM approach to maintenance ensures that the proper type of maintenance is performed when it is needed. This results in an increased availability and a higher percentage of fully mission capable equipment.

4. RCM Categories

There are four RCM categories: run-to-failure, preventive maintenance, predictive maintenance and proactive maintenance.

a. Run-to-Failure

Run-to-failure works on the assumption that it is most cost effective to let equipment run unattended until it fails. It is based on the idea that "if it is not broken, do not fix it". An equipment receives maintenance only when a functional failure has occurred. This method also assumes that failure is equally likely to occur in any part, component or system. Therefore characterizing some repairs as more critical or more necessary than others, is precluded under this RCM category.

This method requires the least support and the equipment is run with very little or no attention or monitoring. The major drawback of run-to-failure is the unexpected and unscheduled equipment downtime. When something fails catastrophically or can no longer perform its function, it must simply be replaced. However if the repair parts are not available, serious logistical problems and unexpected costs can occur. Cannibalization of like equipment may satisfy a temporary need, but at substantial costs. Labor and materials are also used inefficiently under this method. Labor resources are thrown at whatever breakdown is most pressing. Replacement parts must be constantly stocked at high levels, since there is no failure rate prediction, and this means higher capital and carrying costs. The end result is a low operational availability.

Run-to-failure can be effective only when used selectively and performed as a conscious decision based on an RCM analysis. That way, the risk of failure and the cost of maintenance required to mitigate that risk would have been thoroughly analyzed and compared.

Run-to-failure is still being used in many cases in aircraft maintenance. As indicated in Chapter III, this is especially true for aircraft wiring maintenance with the predominant philosophy being "fly to failure".

b. Preventive Maintenance

Preventive maintenance is also referred to as time-driven or calendar-based maintenance. It comprises of maintenance tasks on a piece of equipment at regular intervals whether the equipment needs it or not. It is performed without regard to equipment condition or degree of use.

Preventive maintenance involves the periodic checking of the performance or condition of the component to detrmine if its operating condition and degradation rate are within expected limits. If the findings indicate that the degradation rate is more rapid than anticipated, the problem must be found and corrected before equipment failure occurs. Mean-Time-Between-Failures (MTBF) is a parameter often used to set schedules. [Ref. 20]

When well implemented, preventive maintenance may produce savings in excess of 25 percent [Ref.20]. Beyond a certain point, the gain approaches a point of diminishing returns. Moreover, preventive maintenance is very labor-intensive and often involves unneeded maintenance. Even though it is an improvement over run-to-failure, unscheduled downtime is still a consideration.

c. Predictive Maintenance

Predictive maintenance, also known as condition monitoring, is aimed at detecting the degradation mechanisms themselves and eliminating or controlling them before any significant physical deterioration of the equipment occurs. It uses nonintrusive testing techniques, visual inspection, and performance data to assess equipment condition. It replaces arbitrarily timed maintenance tasks with maintenance scheduled only when warranted by equipment condition.

The main benefit of predictive maintenance is the earlier warning that reduces the number of breakdown failures. Continuing analysis of equipment condition monitoring data, allows planning and scheduling of maintenance or repairs in advance of catastrophic and functional failures.

Predictive maintenance does not lend itself to all types of equipment or possible failure modes and therefore should not be the sole type of maintenance practiced. [Ref. 21]. The best results are achievd when its is implemented concurrently with preventive maintenance.

d. Proactive Maintenance

A proactive maintenance program is the capstone of RCM philosophy. It provides a logical culmination to the other types of maintenance described above (run-to-failure, preventive and predictive). Proactive maintenance improves maintenance through

better design, installation, maintenance procedures, workmanship, and scheduling.[Ref. 21]

This approach replaces the maintenance philosophy of failure reactive with failure proactive by avoiding the underlying conditions that lead to machine faults and degradation. It is an important tool to cure failure root causes and extend the components life. Unlike predictive/preventive maintenance, proactive maintenance looks at failure root causes, not just symptoms. Its main goal is to extend equipment life as opposed to: (1) making repairs when they are often not needed, (2) accommodating failure as routine and normal, (3) pre-empting crisis failure maintenance.[Ref. 20]

Expert system software combined with strategically located sensors and transducers (pressure, temperature, vibration, moisture etc.) can provide comprehensive equipment health monitoring for almost every system and component.

C. RCM APPLIED IN AGING AIRCRAFT WIRING

1. Scope of the Analysis

The urgency for an aging wiring proactive management plan was widely discussed in Chapter III. RCM will be used to satisfy this need. The application of the RCM logic in aging wiring will produce a new, effective and efficient methodology to manage and maintain wiring system.

The two main components of an RCM program are the reliability data (e.g. MTBF) and the analysis process. The focus of this thesis will be the second one.

Determining reliability data for aging wiring is an extremely difficult mathematical and engineering endeavor. In fact only during recent years, some attempts to establish aircraft wiring reliability data through studies made by academic organizations, have occured. The U.S. Air Force together with private industry, has also performed a similar study, the results of which are classified [Ref. 23]. But still, there is a long way until we have consistent and scientifically proved reliability data for each one of the various types of wiring used in aircarfts.

In the following pages, a detailed and analytical way will be presented, which can be used by military aviation maintenance in order to determine if an aircraft wiring needs proactive maintenance and what kind, redesign or simply replacement. This process will be RCM based and it will eventually result in cost savings (through timely and efficient maintenance), higher operational availability and ultimately increased aircraft safety.

2. RCM Process

a. General

The RCM process that will be followed, is summarized by the following steps (Figure 9):

- Functional Failure Analysis: Defines equipment functions and functional failures.

- Significant Item (SI) Selection: establishes which components and systems will be analyzed and establishes the component or function as either structurally or functionally significant.

- RCM Decision Logic: determines failures consequences, maintenance changes and potential redesign requirements for significant items.

- Age Exploration (AE) Analysis: determines data gathering tasks needed to support the RCM analysis.[Ref. 24]

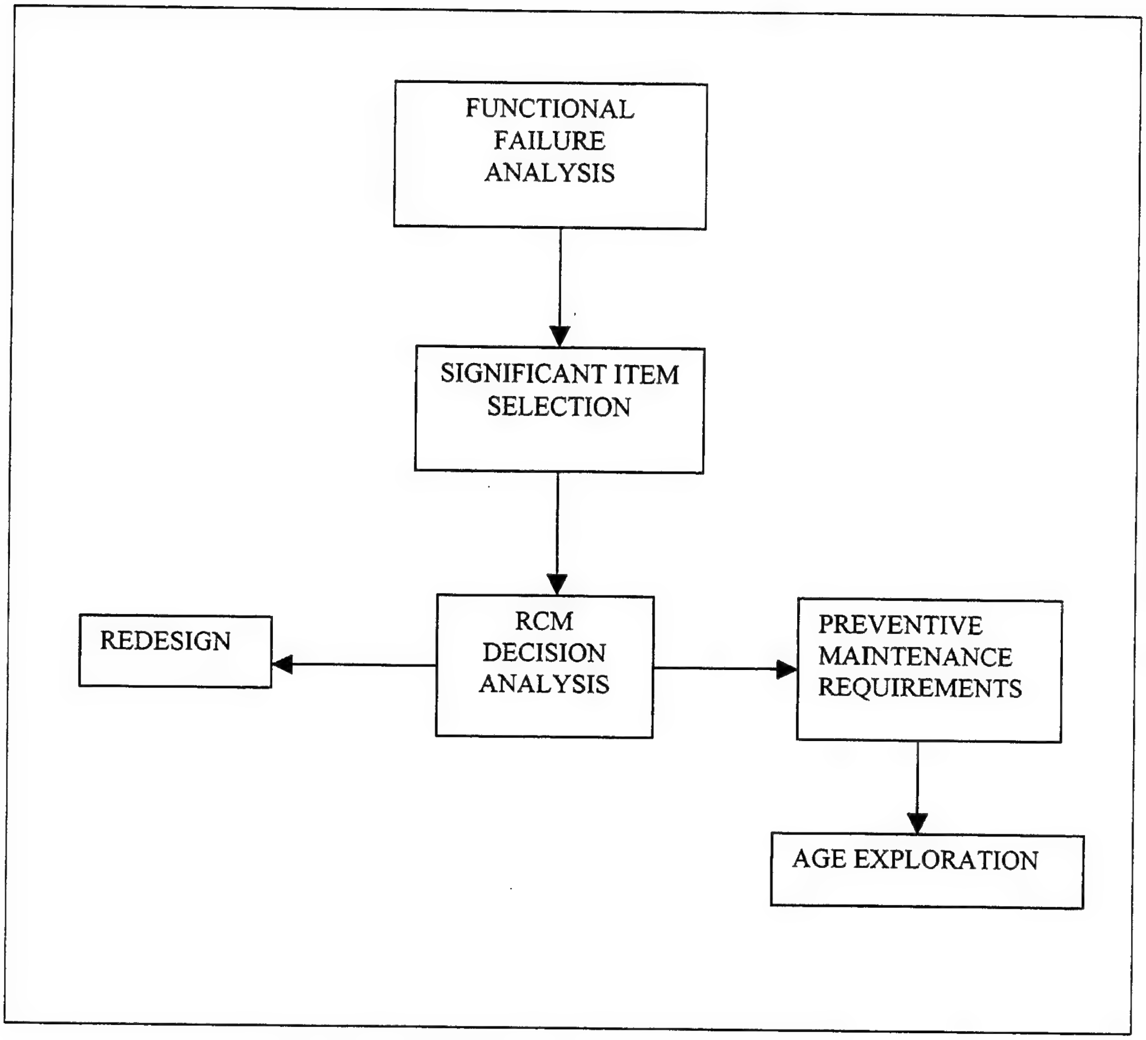

Figure 9. RCM Analysis Process From [Ref. 24]

b. Functional Failure Analysis

As previously discussed, aging wiring failures are primarily detected visually. Aircraft wiring faults can be short and open circuits,bad connections, intermittent or open solder connections, crimped or frayed wires, broken shields, cocked connectors, water and moisture in harnessing and many others. If the wiring is part of a critical aircraft system (e.g. flight control) then the wiring failures are considered a safety

issue. Even if the wiring is located in a non critical system, the wiring failures can still be considered safety related, since they can always lead to fires during flight.

c. *Significant Item Selection*

Significant items are divided into three categories: structural, functional and non-significant. The logic, in order to determine in which category a specific wiring harness falls, is shown in Figure 10.

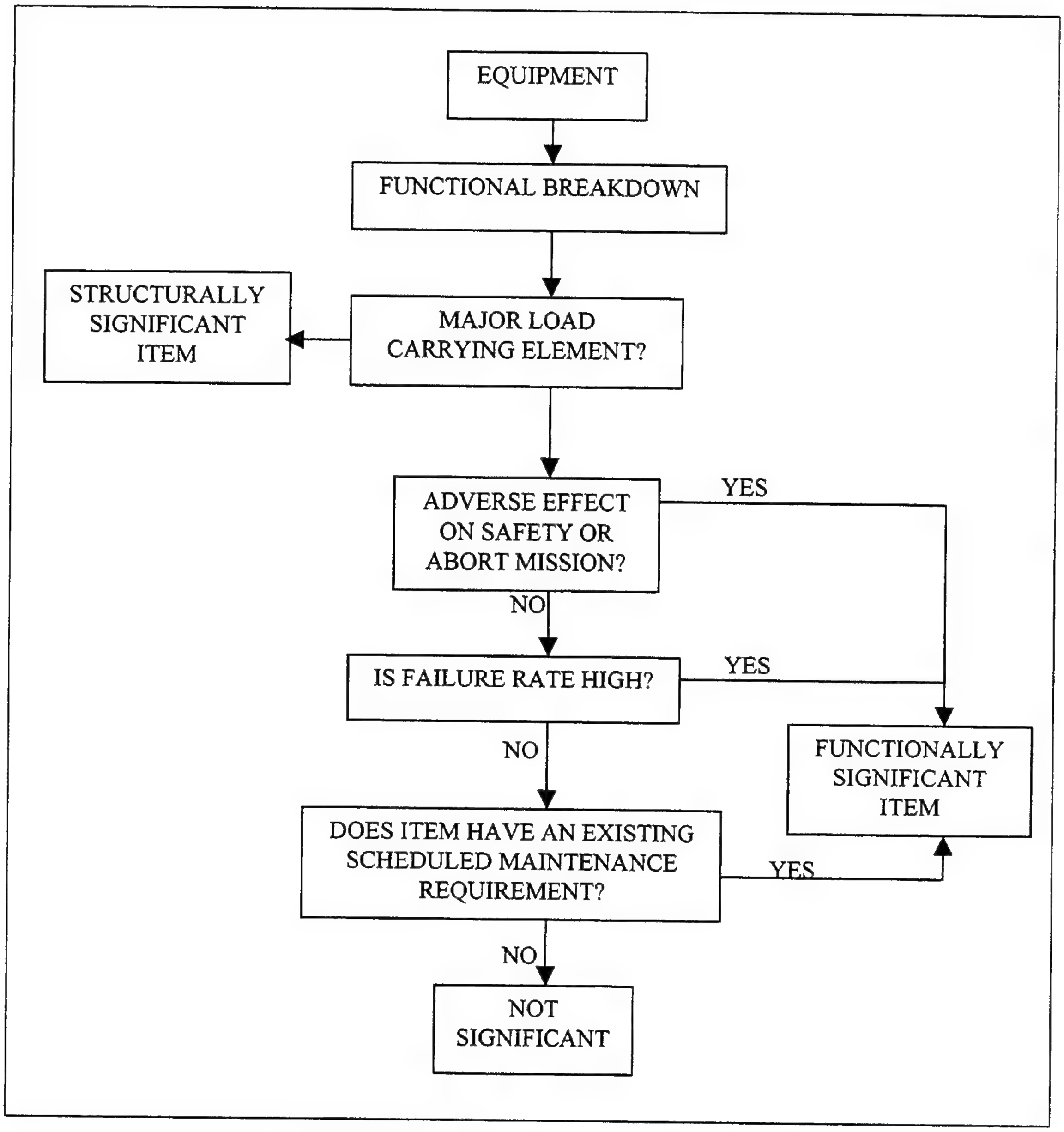

Figure 10. FSI Decision Diagram From [Ref. 24]

There are four questions that should be answered during this process:

- Does the function of wiring carry major ground or aerodynamic loads?
- Does a wiring failure cause an adverse effect on aircraft safety?

- Is the failure rate high?
- Does aging aircraft wiring have an existing preventive maintenance requirement?

Although aging wiring can also be classified as a structurally significant item, since it exhibits crack and wear propagation and is exposed to accidental damage, a classification as a functionally significant item seems more appropriate. Indeed, many aircraft wiring harnesses (flight control wiring, fuel tank wiring) could have an adverse effect on safety and almost every wiring failure could result to abort a mission. Moreover, as indicated in Chapter III, there is no existing preventive maintenance schedule besides the Built-In-Test which is a general test and usually cannot detect potential wiring problems. Therefore, the answers in the second and fourth question lead to the conclusion that aging aircraft wiring should be analyzed as a functionally significant item (no definite answer can be given in the third answer as no determined wiring failure data exist. Nevertheless the answer in this question does not affect the final conclusion).

d. RCM Decision Analysis

Having performed the functional failure analysis and the significant item selection, the next and most important step in the RCM analysis is the RCM decision logic. It is a systematic approach for evaluating aircraft systems and components to determine preventive maintenance requirements. The decision logic will analyze and evaluate preventive maintenance tasks for applicability and effectiveness. Applicability

determines if the task is appropriate for preventing the failure mode, and effectiveness determines if the task can be performed at some in interval that will reduce the probability of failure to an acceptable level.[Ref. 25]

The logic, shown in Figure 11, consists of two levels. At the first level, the logic separates the hidden from the evident functional failures and determines the consequences of failure and the necessity to perform a preventive maintenance task. At the second level, the logic determines applicable and effective maintenance tasks.

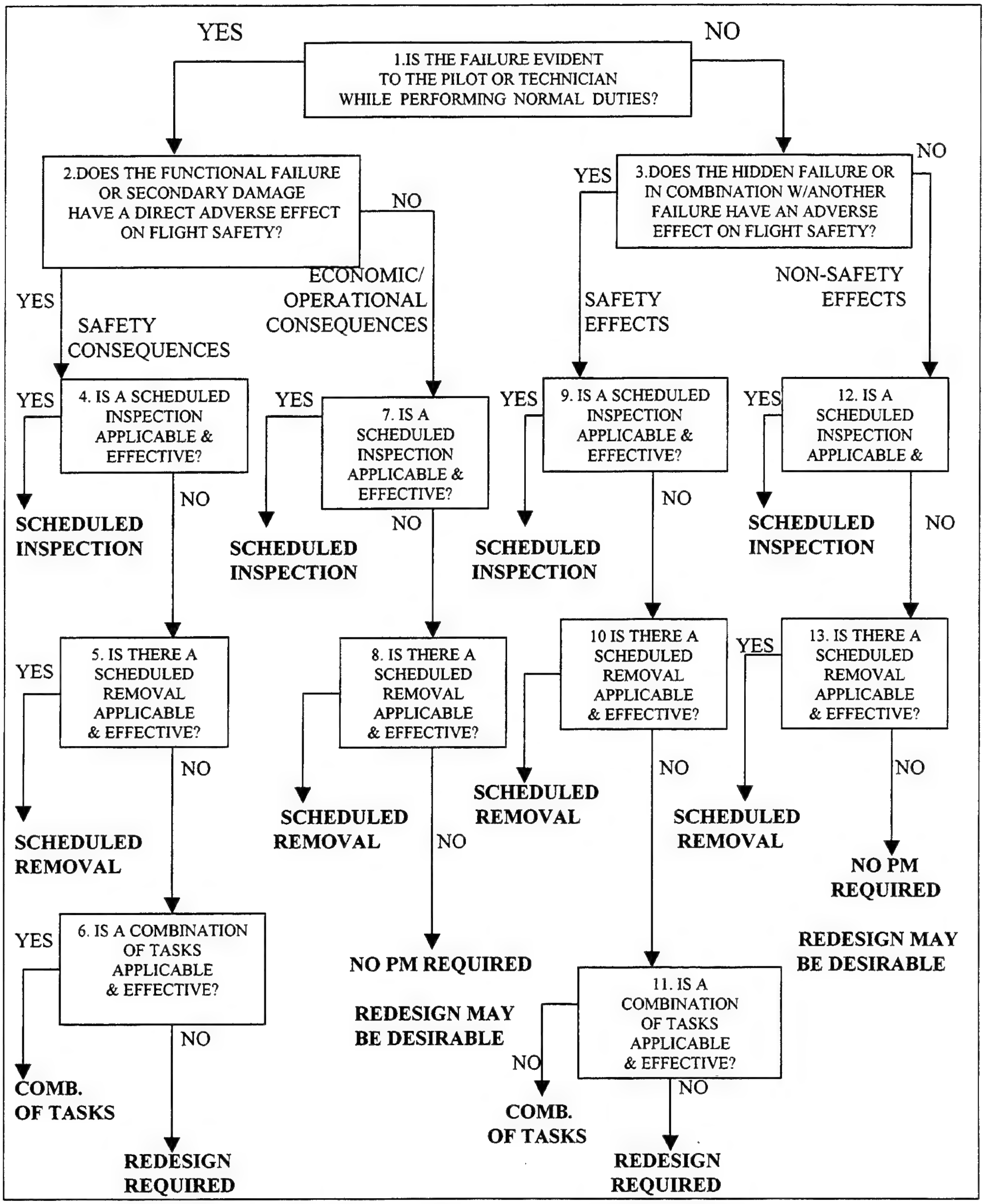

Figure 11. RCM Decision Logic Tree for Aircraft Wiring From[Ref. 26]

The first question asked is, if the occurrence of a functional failure is evident to the pilot or the technician while performing normal duties. This question should be asked for each functional failure of the aircraft wiring. The objective is if the pilot or the technician will be aware of the loss of the function during the performance of their normal duties. Aging wiring failures may or may not be evident. Some failures can be detected through visual inspection by the maintenance crew or reported by the pilot. However, there are many more wiring failures that are undetectable (hidden) either because some wiring harnesses are located in inaccessible areas that are not visually inspected during regular maintenance or simply because there is no mechanism for warning the pilot or the technician of wiring chaffing and wear. Thus, the answer can either be "yes" or "no".

If the answer to the first question is "yes", we then move to question two. The second question is if the functional failure or secondary damage, resulting from the functional failure, has an adverse effect on aircraft safety. This question evaluates the consequences of failure for situations involving safety of flight. In order to have an adverse effect on flight safety, the consequences must be extremely serious or possibly catastrophic, with potential injury to aircraft crew or extensive damage to the aircraft.

Again the answer to this question can go both ways. In the case of "yes", that is the failure will have an adverse effect, then the consequences are safety ones. Moving down to this path of the logic tree, there are several alternatives solutions being suggested. Performing a scheduled visual inspection is rejected since this way of

maintaining wiring has proved inadequate. The option of just replacing a wiring harness with a new one is also rejected as this option will dramatically increase downtime, maintenance time and costs without eliminating the failure cause. The alternatives left are two. The first one is establish a preventive maintenance process for aging wiring consisting of a combination of tasks. These tasks can be a scheduled inspection of wiring harness (based on intervals defined by the failure rates) along with the installation of monitoring equipments, which will provide a wiring failure prognosis, and the replacement of the harness after an established time limit (based again on failure data). The second alternative is the redesign of the wiring harness in question.

If the answer to the second question is "no", then the failure consequences are operational or economical. This means that there are no safety effects. The consequences may affect operational availability or increase the maintenance costs. In this case the suggested solution is a scheduled visual inspection. The option of replacing a wiring harness with a new one is rejected for the same reason as above. The wiring redesign may also be desirable, although the non-criticality of the wiring suggests that this could be an expensive and unnecessary solution.

Having analyzed the alternatives for safety critical failures, we go back to the first question and start the logic tree process all over again but this time following the path when the answer is " no". The next question asked is if the hidden functional failure or the combination with another one, have an adverse effect on safety of flight. This

question evaluates the failure modes that contribute to a functional failure that is not evident to the aircraft pilot. As previously, the answer can be either “yes” or “no”.

If the answer is “yes”, the consequences are safety hidden. The process flow in this case is identical to the one followed for the evident safety failures, and therefore the results are the same: combination of preventive maintenance tasks or wiring harness redesign.

When he answer is “no”, the consequences become non-safety hidden (either mission capability or economics of maintenance). The path is the same, as for the evident non-safety failures, and the result is a scheduled visual inspection.

e. Age Exploration

The last task in the RCM process, is the Age Exploration. It provides a methodology to vary key aspects of the maintenance program in an attempt to optimize the maintenance process. Age exploration analysis determines data gathering tasks needed to support the RCM analysis. Tasks are developed to collect data in order to refine default decisions or data included in the initial RCM analysis.

A preventive maintenance program remains in a dynamic state throughout the life of the equipment. To maintain an efficient preventive maintenance program, field data must be collected and analyzed. The process for collecting data from operational experience is given by Age Exploration (AE) analysis. AE procedures supply the information needed to determine the applicability and evaluate the effectiveness of maintenance tasks. The information derived from AE is directed towards the optimization

of existing maintenance intervals and procedures. This information includes the types of failures aircraft wiring exhibits, ages at which specific failures are exhibited, consequences of failures. AE utilizes statistical methods to collect data from field units. Mathematical techniques are then used to process the data to obtain the desired relationships between age and reliability.

Age exploration can be used in aging aircraft wiring by determining the maintenance time intervals. One of the results of the RCM decision analysis that we previously followed, was a scheduled visual inspection. The time interval between theses inspections can be determined by the Age Exploration analysis. By examining the ages at which specific failures are exhibited and by employing mathematical models, AE can relate age with reliability and determine the optimum time interval. Then, AE analysis will lengthen the time intervals between regular inspections, and subsequently record the effects of lengthening those time intervals.

In order to have an effective AE program, sufficient and valid maintenance data are needed. It is essential that data be available to gauge the success of the AE effort. Examples of these data are history of wiring failures by aircraft serial number and wiring harness part number, history of maintanance activity in every wiring harness, flight hours for every wiring harness etc. The existence of a detailed and updated maintenance database concerning aircraft wiring is a very important prerequisite for a successful AE analysis, especially given the fact that there is a lack of maintenance-related information (either it does not exist, it cannot be assessed when required or at times it cannot be put

together to take a meaningful decision). The Aircraft Wiring Information System Database which was developed by the U.S. Navy, is still at a beginning stage but it is a very good example of a detailed database which can be used in complicated tasks like RCM analysis or Age Exploration program [Ref.27].

3. Results

The RCM logic tree was followed in order to analyze the aircraft wiring failure process and to devise a preventive maintenance plan. The final recommendations depend on the type and criticality of failure.

Specifically, if the wiring failure is evident to the crew or technician (cockpit indication, fire, or a severe wiring wear) and it affects flight safety (flight control wiring, engine wiring, landing gear wiring) then the recommendations are *a combination of preventive maintenance tasks* or *wiring harness redesign*. The same recommendations also apply in the case of failures that are not evident but do affect flight safety.

If the the wiring failure is evident to the crew and it only affects mission accomplishment (radar wiring, weapons release wiring), not flight safety, the recommendation *is a scheduled visual inspection.* Scheduled visual inspection is also recommended when the failure is not evident but the consequences are not safety-related.

The most important observation in this process is that the final recommendations are based on the type of wiring examined. Therefore, the wiring location and the wiring criticality concerning aircraft safety, will ultimately decide the

type of action to be taken. Every aging wiring harness should be analyzed as shown previously in order to determine an appropriate preventive maintenance action.

Another interesting point is that visual inspections should continue to take places in the cases indicated by the RCM logic. Despite the fact that they are not very effective, they remain the best solution when flight safety is not adversely affected.

Finally, the wiring redesign is a recommendation focused on the manufacturers and not on the maintenance personnel. As already discussed in Chapter III, design is one of the most important causes of aging wiring failure. The RCM logic identified wiring redesign as one of the solution. This should come as no surprise because, as already mentioned, the RCM process provides a feedback loop coming from the maintenance personnel who gather data from the successes/failures and feed these data back to improve system design.

The above analysis provides a systematic approach for evaluating the failure consequences of aging wiring and implementing a proactive maintenance plan. This framework can then be used by maintenance managers to analyze the type of wiring and the type of failure they are interested in and come up with a program fitted to their needs.

D. TECHNICAL SOLUTIONS

1. General

In order to establish a general management plan for aging aircraft wiring, we had to follow the RCM decision analysis. This analysis and specifically the RCM logic tree, led to several recommendations. One of those recommendations was a combination of tasks including the use of monitoring equipment to aid in the prognosis of wiring failure.

There are several technical solutions, like the one recommended from the RCM logic, developed by the private industry in accordance with the military. These technical solutions along with the maintenance plan devised by RCM can assist in achieving a predictive aging wiring maintenance. Some of these solutions will be analyzed next.

2. Smart Wiring

Smart wiring is a project developed to measure and monitor the degradation in aircraft wiring over time. The smart wiring measurement system is made with embedded processors and microsensors. The embedded processor uses model based reasoning techniques to model the wiring system performance stored in a memory chip. Model based reasoning provides software prognostics and services to assist in proactively managing the health of aging aircraft wiring systems.

Because it is necessary to access circuit wires individually, the sensors reside directly behind the connector. In most cases the sensors are housed in what would

essentially be a large electromagnetic interference backshell and thus become an innocuous part of the wiring harness.[Ref. 18].

The sensors weigh just a few ounces using Micro Machined Electromechanical Systems (MEMS) and Application Specific Integrated Circuits (ASIC) that weigh just a few milligrams each. Also, an infrared (IR) link at the connector interface is used to retrieve data. The information obtained from the sensors are available for either on-board or off-board analysis and are used by prognostic algorithms to determine the health of the wiring.

There are many benefits to the use of smart wiring. Technicians will be directed to exact locations of shorts and open conditions rather than using current labor intensive methods. The smart systems can also monitor the units attached to the wiring and monitor whether a unit is failed or working. The smart wiring is also able to monitor performance after reinsertion to assure return to original condition. Smart wiring can thus be very effective in preventing the occurrence of problems through early warnings to the crew and the technicians therefore enabling proactive maintenance.

3. Non-Destructive Wiring Inspection Methods

The military has funded many programs that were aimed at implementing and validating non-destructive wiring inspection techniques. Indeed several of them have come up with very successful results.

In most of the cases, there is usually a field-deployable portable test system consisting of a miniaturized viewing device and controllable uniform illumination mounted in a flashlight-sized portable hand-held unit weighing less than a pound. The device enables real-time in-situ inspection of either a partial view of the surface (or the entire 360-degree surface, as-desired) and recording of the defects and anomalies present. Insulation defects (metallic inclusions, cracks, chafes, cuts) finer than a human hair can be easily seen, discriminated and instantaneously recorded if the inspector wishes to do so. The simultaneous inspection of the entire 360-degree surface of a cable or wire bundle is accomplished via multiple images, regardless of twists and turns in a wire inside the cable or the bundle. In this manner, absolutely no spot goes undetected and there is no possibility of error due to operator fatigue or negligence. Moreover, images and data analysis can be stored on a diskette, which permits an instantaneous comparative evaluation, even in the field.[Ref. 28]

These inspection methods are primarily based on infrared thermography and optical imaging. Infrared thermography detects temperature gradients created by defects such as cuts, cracks, abrasion as thermal energy passes through these defects. Deviation in the thermal response at a point with respect to the preceding one is detected and transmitted to the processing computer.[Ref. 28] Optical imaging methods are a natural outgrowth of the infrared concept and they do not require any thermal excitation.

Non-destructive inspection techniques can replace visual inspections and provide reliable test methods, capable of accurately detecting defects anywhere in the insulation (on the surface or embedded).

4. Arc Fault Circuit Interrupters

As already discussed in Chapter III, the primary device for protecting an aircraft from the hazards of electrical malfunctions, is the circuit breaker. Ordinary circuit breakers are heat sensitive bimetal elements that trip only when a large current passes through the circuit long enough to heat the element. However, a single arc fault that lasts a few milliseconds, will not trip the circuit breaker. Fires have been known to break out with the breaker still intact. That is why a great effort has been expended in trying to come up with new and more effective circuit breakers.

The new arc-fault circuit breakers contain sophisticated electronics to sample the current on the wire at submillisecond intervals. Time and frequency domain filtering techniques are used to extract the arc fault signature from the current waveform. This signature may be integrated over time to discriminate, by means of pattern matching algorithms, between a normal current and a sputtering arc fault current. Thus, ordinary transients (e.g. a motor being turned on and off) can be distinguished from the random current surges that occur with arcing.[Ref.7]

Although the research on these circuit breakers is still underway, the benefits of the arc fault circuit interrupters will not only be in terms of maintenance cost and time but also in flight safety.

V. CONCLUSIONS AND RECOMMENDATIONS

A. INTRODUCTION

Aging aircraft wiring presents a difficult and complicated problem for the military and commercial aviation. Recent accidents in both the commercial and military aviation have made clear that the effects of age on aircraft wiring can really be catastrophic. As aircraft are being utilized long beyond their intended life, more complications due to aging wiring become apparent.

Aging wiring imposes a nightmare for aircraft maintenance. Wiring-related problems are a leading cause of unscheduled maintenance hours for aircraft. A significant portion of aircraft maintenance man-hours is expended in troubleshooting wiring to effect repairs. In addition, current maintenance procedures do not handle effectively the aging wiring problem.

Therefore, the concept of Reliability Centered Maintenance was used to construct a proactive management plan. This chapter provides the conclusions and recommendations of this effort.

B. CONCLUSIONS

1. Aircraft Wiring Ages and Degrades Over Time

All electrical wire systems are subject to aging: the progressive deterioration of physical properties and performance of wire systems with use and with the passage of time. Several factors such as exposure to the atmosphere, vibration, heat, water intrusion, corrosion, wiring design and installation, contribute to the aging process.

This wire degradation is cumulative over time. Therefore, when the number of flying hours increases, the occurrence of wire degradation also gets higher. As an aircraft ages, the number of wire defects increases.

2. Aging Wiring Severly Impacts Aircraft Safety

Short circuits and arc tracking are some of the effects of aging wiring . Both of these two conditions have been implicated in many serious accidents (TWA 800 and Swiss Air 111, Apollo 1). Moreover, from July 1995 to December 1997, the U.S. Navy experienced 64 in-flight electrical fires caused by short circuits and arc tracking.

Thus, aging wiring is a very serious problem which can lead to loss of critical aircraft systems, on board fires and consequently loss of an aircraft.

3. Current Maintenance Practices do not Adequately Address Wiring

The predominant maintenance philosophy for wiring, is “fly to fix”. Once it has failed, it is then repaired or replaced and the aircraft returns to service.

Today's typical wiring inspections are visual and they do not get to the heart of aircraft wiring problems. Obvious failures such as severed wires are detected, but individual visual inspections do not reveal the slow but continuous erosion of wiring that results from thousands of bumps and jolts in the aircraft's lifetime.

Current maintenance practices fall short in successfully inspecting and maintaining wiring. There is an apparent lack of an effective and efficient methodology to manage and maintain aging wiring system anomalies.

C. RECOMMENDATIONS

1. RCM Analysis Should be Followed for Every Type of Wiring

The RCM logic tree was followed in order to analyze the aircraft wiring failure process and to devise a preventive maintenance plan. The final recommendations that we came up with are not universal but depend on the type and criticality of the failure. Therefore, the recommendations for a wiring that affects flight safety (e.g. flight control wiring, engine wiring, landing gear wiring) are not the same as the ones targeted for a wiring failure which only affects mission accomplishment (radar wiring, weapons release wiring).

The RCM analysis we suggested, provides a systematic approach for evaluating the failure consequences of aging wiring and implementing a proactive maintenance plan. This framework can then be used by maintenance managers to analyze the type of wiring

and the type of failure they are interested in and come up with a program fitted to their needs.

2. An Accurate Wire Discrepancy Data Collection System Needs to be Established

There is a lack of maintenance-related information in the military. Especially, the collection of wiring maintenance data is a task that little has bothered the military aviation. But in order to have an effective RCM program, sufficient and valid maintenance data are needed. The existence of data like history of wiring failures by aircraft serial number and wiring harness part number, history of maintenance activity in every wiring harness, flight hours for every wiring harness and other, is a very important prerequisite for a successful proactive management plan. Initiatives like the U.S. Navy Aircraft Wiring Information System Database, can provide a benchmark for the development of a detailed and updated maintenance database concerning aircraft wiring.

3. Technical Solutions Can Assist in a Proactive Management Plan

The private industry and the military have taken significant steps in developing technical solutions that advance the proactive maintenance of aging wiring. Projects that are capable of monitoring the wiring health (smart wiring), circuit breakers that can detect arc faults or new non-destructive wiring maintenance techniques should be a part of a detailed and rigorous proactive wiring maintenance plan.

LIST OF REFERENCES

1. Brannen, E., "The Problem of Aging Aircarf: *Is Mandatory Retirement the Answer*?", *Journal of Air Law and Commerce*,v.57, pp. 425-467, Winter 1991.

2. Committee on Aging of U.S. Air Force Aircraft, National Materilas Advisory Board, Commission on Engineering and Technical Systems, National Research Council, *Aging of U.S Air Force Aircraft Final Report*, National Academy Press, 1997.

3. Brown,M. and Teal,C., "Automated System Quality Assurance", White Paper, 1998.

4. Massenburg,W.B., "Maintaining Yesterday's Weapons for Tomorrow's Warfighter", White Paper, July 2000.

5. Nieto,M.E., *Naval Aviation Aging Wiring: Prognostic and Diagnostic Solutions*, Master's Thesis, Naval Postgraduate School, Monterey, California, December 2000.

6. U.S. Department of Transportation, Federal Aviation Administration Technical Center, *Program Plan: National Aging Aircraft Research Program*, National Technical information Service, 1991.

7. Furse,C. and Haupt,R., "Down to the Wire", IEEE Spectrum Online, February 2001.

8. Testimony of Loeb,B. Director Office of Aviation Safety, National Transportation Safety Board, before The House of Representatives Subcommitee on Oversight, Investigations and Emergency Management, 15 September 1999.

9. Smith,C. and Hughes, W., "FAA Aging NonStructural Systems Research", White Paper, 1998.

10. Blemel, K. and Blemel, P., "Smart Wiring prognostic Health Management", 1998.

11. Statement of Berlin J.E. before The House of Representatives Subcommitee on Oversight, Investigations and Emergency Management, 15 September 1999.

12. Engel,J., Waz,M. and McCormick,J., "Arc Fault Circuit Interrupters", White Paper, 2000.

13. Adams,K., "Ticking Faults", White Paper, 1998.

14. McMahon,R., Smith,G., Schroeder,J. and Beach,R., “Organized Wiring:21st Century Aircraft Infrastucture Backbone”, White Paper, 2000.

15. Lee, D., and Arnason,P., “USN Wiring Systems Lessons Learned”, White Paper, 2000.

16. Milliman,J., “Engineers, industry tackle aging aircraft wiring risk”, *dcmilitary.com*, 28 September 2000.

17. Sullivan,S. and Slenski,G., “Managing Electrical Connection Systems and Wire Integrity on Legacy Aerospace Vehicles”, White paper, 2000.

18. Smith,G., Schroeder,J., Blemel,K. and McMahon,R., “Prognostics for Wiring: Managing the Health of Aging Wiring Systems”, White Paper, 1999.

19. Statement of Dr Bruning before the House of Representatives Subcommitee on Oversight, Investigations and Emergency Management, 15 September 1999.

20. Construction Engineering Research Laboratory Technical Report 99/50, *Streamlined Reliability Centered Maintenance*, by A.Chalifoux, J.Northrup and N.Chan, May 1999.

21. Construction Engineering Research Laboratory Technical Report 99/41, *Reliability Centered Maintenance:Operating a More Effective Maintenance Program*, by A.Chalifoux and J. Baird, April 1999.

22. Eaton,D. RADM, “Reliability Centered Maintenance”, Lecture Slides for MN4470 Course at the Naval Postgraduate School, Monterey, California.

23. Air Force Contract #F33615-95-C-5620 Final Report, *Life Prediction of Aging Aircraft Wiring System*, by Yogesh Mehrotra, December 1995.

24. King,M.F., *A Reliability Centered Maintenance Analysis of Aircraft Control Bearings*, Master’s Thesis, Naval Postgraduate School, Monterey, California, December 1997.

25. Department of the Navy,Commander,Naval Air Systems Command,NAVAIR Manual 00-25-403, “Guidelines for the Naval Aviation RCM Process”.

26. U.S. Coast Guard, *Reliability Centered Maintenance Proces*, CGTO PG-85-00-30, Revision A, 1 May 1997.

27. Hubbard,R. and Kowalski,T., “Aircraft Wiring Information System (AWIS) Database”, White Paper, 2000.

28. Mehrotra,Y. and Pike,J., "Wiring and Cable Inspection: It is Scientific, Not Magic", White Paper, 1998.

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